PREFERRED EMBODIMENT TO LED LIGHT STRING

CROSS REFERENCES TO RELATED APPLICATIONS

This application is a continuation-in-part of copending application serial number 09/378,631 filed August 20, 1999, titled Preferred Embodiment to Led Light String, which is a continuation-in-part of copending application serial number 09/339,616 filed June 24, 1999, titled Preferred Embodiment to Led Light String, which is a continuation-in-part of copending application serial number 09/141,914 filed August 28, 1998, titled Led Light String Employing Series-parallel Block Coupling. The disclosures of the aforementioned applications are incorporated herein by reference. This application claims benefit of U.S. Provisional Application No. 60/119,804, filed February 12, 1999.

BACKGROUND OF THE INVENTION

1. Field of Invention

The present invention relates to light strings and, more particularly, to decorative light strings employing LEDs.

2. Description of Related Art

Light emitting diodes (LEDs) are increasingly employed as a basic lighting source in a variety of forms, including decorative lighting, for reasons among the following. First, as a device, LEDs have a very long lifespan, compared with common incandescent and fluorescent sources, with typical LED lifespan at least 100,000 hours. Second, LEDs have several favorable physical properties, including ruggedness, cool operation, and ability to operate under wide temperature variations. Third, LEDs are currently available in all

primary and several secondary colors, as well as in a "white" form employing a blue source and phosphors. Fourth, with newer doping techniques, LEDs are becoming increasingly efficient, and colored LED sources currently available may consume an order of magnitude less power than incandescent bulbs of equivalent light output. Moreover, with expanding applications and resulting larger volume demand, as well as with new manufacturing techniques, LEDs are increasingly cost effective.

LED-based light strings, used primarily for decorative purposes such as for Christmas lighting, is one application for LEDs. For example, U.S. patent 5,495,147 entitled LED LIGHT STRING SYSTEM to Lanzisera (hereinafter "Lanzisera") and U.S. patent 4,984,999 entitled STRING OF LIGHTS SPECIFICATION to Leake (hereinafter "Leake") describe different forms of LED-based light strings. In both Lanzisera and Leake, exemplary light strings are described employing purely parallel wiring of discrete LED lamps using a step-down transformer and rectifier power conversion scheme. These and all other LED light string descriptions found in the prior art convert input electrical power, usually assumed to be the common U.S. household power of 110 VAC to a low voltage, nearly DC input.

SUMMARY OF THE INVENTION

The present invention relates to a light string, including a pair of wires connecting to a standard household AC electrical plug; a plurality of LEDs powered by the pair of wires, wherein the LEDs are electrically coupled in series to form at least one series block; multiple series blocks, if employed, that are electrically coupled in parallel; a

standard household AC socket at the opposite end for connection of multiple light strings in an end-to-end, electrically parallel fashion.

It is an object of this invention to provide a method and preferred embodiment that matches the AC voltage rating of the LEDs coupled in series to the AC power input without the need for additional power conversion.

The present invention relaxes the input electrical power conversion and specifies a preferred embodiment in which the LED light string is electrically powered directly from either a common household 110 VAC or 220 VAC source, without a different voltage involved via power conversion. The LEDs may be driven using household AC, rather than DC, because the nominal LED forward bias voltage, if used in reverse bias fashion, is generally much lower than the reverse voltage where the LED p-n junction breaks down. When LEDs are driven by AC, pulsed light is effected at the AC rate (e.g., 60 or 50 Hz), which is sufficiently high in frequency for the human eye to integrate and see as a continuous light stream.

BRIEF DESCRIPTION OF THE DRAWINGS

Other aspects, features and advantages of the present invention will become more fully apparent from the following detailed description, the appended claims, and the accompanying drawings in which:

FIGS. 1A and 1B show two example block diagrams of the light string in its embodiment preferred primarily, with one diagram for a 110 VAC common household input electrical source (e.g., 60 Hz) and one diagram for a 220 VAC common household (e.g., 50 Hz) input electrical source.

FIG. 2A shows a schematic diagrams of an embodiment of this invention in which the diodes of the 50 LEDs (series) blocks 102 of Fig. 1 are connected in the same direction.

FIG. 2B Shows a schematic diagrams of an embodiment of this invention in which the diodes of the 50 LEDs (series) blocks 102 of Fig. 1 are connected in the reverse direction.

FIGS. 3A and 3B show two example block diagrams of the light string in its embodiment preferred alternatively, with one diagram for a 110 VAC common household input electrical source (e. g., 60 Hz) and one diagram for a 220 VAC common household (e.g., 50 Hz) input electrical source.

FIG. 4 shows an example schematic diagram of the AC-to-DC power supply corresponding to the two block diagrams in FIG. 3 for either the 110 VAC or the 220 VAC input electrical source.

FIGS. 5A and 5B show example pictorial diagrams of the manufactured light string in either its "straight" or "curtain" form (either form may be manufactured for 110 VAC or 220 VAC input).

FIG. 6 shows an example pictorial diagram of special tooling of the housing for an LED housing in the light string, for assurance of proper LED electrical polarity throughout the light string circuit.

FIG. 7 shows an example pictorial diagram of special tooling and manufacturing of the LED and its housing in the light string, for assurance of proper LED polarity using the example in FIG. 6.

FIG. 8 shows an example pictorial diagram of a fiber optic "icicle" attached to an LED and its housing in the light string, where the "icicle" diffuses the LED light in a predetermined manner.

FIG. 9 is a graph of current versus voltage for diodes and resistors.

FIGS. 10A and 10B are a schematic and block diagrams of direct drive embodiments.

FIG. 11 is a plot showing the alternating current time response of a diode.

FIG. 12 is a graph showing measured diode average current response for alternating current and direct current.

FIG. 13 is a graph showing measured AlInGaP LED average and maximum AC current responses.

FIG. 14 is a graph showing measured light output power as a function of LED current.

FIG. 15 is a graph showing measured GaAlAs LED average and maximum AC current responses.

FIG. 16 is a graph showing measured GaP LED average and maximum AC current responses.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

The term "alternating current voltage", sometimes abbreviated as "VAC", as used herein occasionally refers to a numerical amount of volts, for example, "220 VAC". It is to be understood that the stated number of alternating current volts is the nominal voltage

which cycles continuously in forward and reverse bias and that the actual instantaneous voltage at a given point in time can differ from the nominal voltage number.

In accordance with the present invention, an LED light string employs a plurality of LEDs wired in series-parallel form, containing at least one series block of multiple LEDs. The series block size is determined by the ratio of the standard input voltage (e.g., either 110 VAC or 220 VAC) to the drive voltage(s) of the LEDs to be employed (e.g., 2 VAC). Further, multiple series blocks, if employed, are each of the same LED configuration (same number and kinds of LEDs), and are wired together along the string in parallel. LEDs of the light string may comprise either a single color LED or an LED including multiple sub-dies each of a different color. The LED lenses may be of any shape, and may be either clear, clear-colored, or diffuse-colored. Moreover, each LED may have internal circuitry to provide for intermittent on-off blinking and/or intermittent LED sub-die color changes. Individual LEDs of the light string may be arranged continuously (using the same color), or periodically (using multiple, alternating CIP colors), or pseudo-randomly (any order of multiple colors). The LED light string may provide an electrical interface to couple multiple lights strings together in parallel, and physically from end to end. Fiber optic bundles or strands may also be coupled to individual LEDs to diffuse LED light output in a predetermined manner.

An LED light string of the present invention may have the following advantages. The LED light string may last far longer and require less power consumption than light strings of incandescent lamps, and they may be safer to operate since less heat is generated. The LED light string may have reduced cost of manufacture by employing series-parallel blocks to allow operation directly from a standard household 110 VAC or

220 VAC source, either without any additional circuitry (AC drive), or with only minimal circuitry (DC drive). In addition, the LED light string may allow multiple strings to be conveniently connected together, using standard 110 VAC or 220 VAC plugs and sockets, desirably from end-to-end.

Direct AC drive of LED light string avoids any power conversion circuitry and additional wires; both of these items add cost to the light string. The additional wires impose additional mechanical constraint and they may also detract aesthetically from the decorative string. However, direct AC drive results in pulsed lighting. Although this pulsed lighting cannot be seen at typical AC drive frequencies (e.g. 50 or 60 Hz), the pulsing apparently may not be the most efficient use of each LED device because less overall light is produced than if the LEDs were continuously driven using DC. However, this effect may be compensated for by using higher LED current during each pulse, depending on the pulse duty factor. During "off" times, the LED has time to cool. It is shown that this method can actually result in a higher efficiency than DC drive, depending on the choice of AC current.

FIG. 1 shows the embodiment of an LED light string in accordance with the present invention, and as preferred primarily through AC drive. In FIG. 1, the two block diagrams correspond to a exemplary string employing 100 LEDs, for either 110 VAC (top diagram) or 220 VAC (bottom diagram) standard household current input (e.g., 50 or 60 Hz). In the top block diagram of FIG. 1, the input electrical interface consists merely of a standard 110 VAC household plug 101 attached to a pair of drive wires.

With the average LED drive voltage assumed to be approximately 2.2 VAC in FIG. 1, the basic series block size for the top block diagram, corresponding to 110 VAC input,

is approximately 50 LEDs. Thus, for the 110 VAC version, two series blocks of 50 LEDs 102 are coupled in parallel to the drive wires along the light string. The two drive wires for the 110 VAC light string terminate in a standard 110 VAC household socket 103 to enable multiple strings to be connected in parallel electrically from end-to-end.

In the bottom block diagram of FIG. 1, the input electrical interface likewise consists of a standard 220 VAC household plug 104 attached to a pair of drive wires. With again the average LED drive voltage assumed to be approximately 2.2 VAC in FIG. 1, the basic series block size for the bottom diagram, corresponding to 220 VAC input, is 100 LEDs. Thus, for the 220 VAC version, only one series block of 100 LEDs 105 is coupled to the drive wires along the light string. The two drive wires for the 220 VAC light string terminate in a standard 220 VAC household socket 106 to enable multiple strings to be connected in parallel from end-to-end. Note that for either the 110 VAC or the 220 VAC light string, the standard plug and socket employed in the string varies in accordance to the country in which the light string is intended to be used.

Whenever AC drive is used and two or more series are incorporated in the light string, the series blocks may each be driven by either the positive or negative half of the AC voltage cycle. The only requirement is that, in each series block, the LEDs are wired with the same polarity; however the series block itself, since driven in parallel with the other series blocks, may be wired in either direction, using either the positive or the negative half of the symmetric AC electrical power cycle.

Figures 2A and 2B show two schematic diagram implementations of the top diagram of FIG. 1, where the simplest example of AC drive is shown that uses two series blocks of 50 LEDs, connected in parallel and powered by 110 VAC. In the top schematic

diagram of FIG. 2A both of these LED series blocks are wired in parallel with the polarity of both blocks in the same direction (or, equivalently, if both blocks were reversed). With this block alignment, both series blocks flash on simultaneously, using electrical power from the positive (or negative, if both blocks were reversed) portion of the symmetric AC power cycle. A possible advantage of this configuration is that, since the LEDs all flash on together at the cycle rate (60 Hz for this example), when the light string flashes on periodically, it is as bright as possible.

The disadvantage of this configuration is that, since both blocks flash on simultaneously, they both draw power at the same time, and the maximum current draw during this time is as large as possible. However, when each flash occurs, at the cycle rate, the amount of light flashed is maximal. The flash rate, a 50-60 Hz, cannot be seen directly by human eye and is instead integrated into a continuous light stream.

The bottom schematic diagram FIG. 2B, shows the alternative implementation for the top diagram of FIG. 1, where again, two series blocks of 50 LEDS are connected in parallel and powered by 110 VAC.

In this alignment, the two series blocks are reversed, relative to each other, in polarity with respect to the input AC power. Thus, the two blocks flash alternatively, with one block flashing on during the negative portion of each AC cycle. The symmetry, or "sine-wave" nature of AC allows this possibility. The advantage if is that, since each block flashes alternatively, drawing power during opposite phases of the AC power, the maximum current draw during each flash is only half of that previously (i.e., compared when both blocks flash simultaneously). However, when each flash occurs, at twice the cycle rate here, the amount of light flashed is reduced (i.e., half the light than if two

blocks were flashing at once as previously illustrated). The flash rate, at 100-120 Hz, cannot be seen directly by the human eye and is instead integrated into a continuous light stream.

The trade-off between reversing series blocks when two or more exist in an AC driven circuit is influenced primarily by the desire to minimize peak current draw. A secondary influence has to do with the properties of the human eye in integrating periodic light flashes. It is well known that the human eye is extremely efficient in integrating light pulses rapid enough to appear continuous. Therefore, the second form of the light string is preferred from a power draw standpoint because the effect on human perception is insignificant.

For AC drive with non-standard input (e.g., three-phase AC) the series blocks may similarly be arranged in polarity to divide power among the individual cycles of the multiple phase AC. This may result in multiple polarities employed for the LED series blocks, say three polarities for each of the three positive or negative cycles.

As an alternative preference to AC drive, FIG. 3 shows two block diagrams that correspond to a exemplary string employing 100 LEDs and DC drive, for either 110 VAC (top diagram) or 220 VAC (bottom diagram) standard household current input (e.g., 50 or 60 Hz). In the top block diagram of FIG. 3, the input electrical interface consists of a standard 110 VAC household plug 301 attached to a pair of drive wires, followed by an AC-to-DC converter circuit 302. As in FIG. 1, with the average LED drive voltage assumed to be approximately 2.2 VAC in FIG. 3, the basic series block size for the top block diagram, corresponding to 110 VAC input, is approximately 50 LEDs. Thus, for the 110 VAC version, two series blocks of 50 LEDs 303 are coupled in parallel to the output

of the AC-to-DC converter 302 using additional feed wires along the light string. The two drive wires for the 110 VAC light string terminate in a standard 110 VAC household socket 304 to enable multiple strings to be connected in parallel electrically from end-to-end.

In the bottom block diagram of FIG. 3, the input electrical interface likewise consists of a standard 220 VAC household plug 305 attached to a pair of drive wires, followed by an AC-to-DC converter circuit 306. With again the average LED drive voltage assumed to be approximately 2.2 VAC in FIG. 3, the basic series block size for the bottom diagram, corresponding to 220 VAC input, is 100 LEDs. Thus, for the 220 VAC version, only one series block of 100 LEDs 307 is coupled to the output of the AC-to-DC converter 307 using additional feed wires along the light string. The two drive wires for the 220 VAC light string terminate in a standard 220 VAC household socket 308 to enable multiple strings to be connected in parallel from end-to-end. Note that for either the 110 VAC or the 220 VAC light string, the standard plug and socket employed in the string varies in accordance to the country in which the light string is intended to be used.

FIG. 4 shows an example schematic electrical diagram for the AC-to-DC converter employed in both diagrams of FIG. 3. The AC input to the circuit in FIG. 1 is indicated by the symbol for an AC source 401. A varistor 402 or similar fusing device may optionally be used to ensure that voltage is limited during large power surges. The actual AC to DC rectification is performed by use of a full-wave bridge rectifier 403. This bridge rectifier 403 results in a rippled DC current and therefore serves as an example circuit only. A different rectification scheme may be employed, depending on cost considerations. For

example, one or more capacitors or inductors may be added to reduce ripple at only minor cost increase. Because of the many possibilities, and because of their insignificance, these and similar additional circuit features have been purposely omitted from FIG. 4.

For either the 110 VAC or the 220 VAC version of the LED light string, and whether or not an AC to-DC power converter is used, the final manufacturing may be a variation of either the basic "straight" string form or the basic "curtain" string form, as shown in the top and bottom pictorial diagrams in FIGS. 5A and 5B. In the basic "straight" form of the light string, the standard (110 VAC or 220 VAC) plug 501 is attached to the drive wires which provide power to the LEDs 502 via the series-parallel feeding described previously. The two drive and other feed wires 503 are twisted together along the length of the light string for compactness and the LEDs 502 in the "straight" form are aligned with these twisted wires 503, with the LEDs 502 spaced uniformly along the string length (note drawing is not to scale). The two drive wires in the "straight" form of the light string terminate in the standard (correspondingly, 110 VAC or 220 VAC) socket 504. Typically, the LEDs are spaced uniformly every four inches.

In the basic "curtain" form of the light string, as shown pictorially in the bottom diagram of FIGS. 5A and 5B, the standard (110 VAC or 220 VAC) plug 501 again is attached to the drive wires which provide power to the LEDs 502 via the series-parallel feeding described previously. The two drive and other feed wires 503 are again twisted together along the length of the light string for compactness. However, the feed wires to the LEDs are now twisted and arranged such that the LEDs are offset from the light string axis in small groups (groups of 3 to 5 are shown as an example). The length of these

groups of offset LEDs may remain the same along the string or they may vary in either a periodic or pseudo-random fashion.

Within each group of offset LEDs, the LEDs 502 may be spaced uniformly as shown or they may be spaced nonuniformly, in either a periodic or pseudo-random fashion (note drawing is not to scale). The two drive wires in the "curtain" form of the light string also terminate in a standard (correspondingly 110 VAC or 220 VAC) socket 504. Typically, the LED offset groups are spaced uniformly every six inches along the string axis and, within each group, the LEDs are spaced uniformly every four inches.

In any above version of the preferred embodiment to the LED light string, blinking may be obtained using a number of techniques requiring additional circuitry, or by simply replacing one of the LEDs in each series block with a blinking LED. Blinking LEDs are already available on the market at comparable prices with their continuous counterparts, and thus the light string may be sold with the necessary (e.g., one or two) additional blinkers included in the few extra LEDs.

In wiring any version of the preferred embodiment to the light string, as described previously, it is critical that each LED is powered using the correct LED polarity. This equates to all feeds coming from the same drive wire always entering either the positive or the negative lead of each LED. Since the drive wires are AC, it does not matter whether positive or negative is chosen initially; it is only important all the LEDs in each series block have the same polarity orientation (either all positive first or all negative first). In order to facilitate ease of proper manufacturing, as well as ease of proper LED bulb replacement by the user, each LED and its assembly into its housing may be mechanically modified to insure proper polarity. An example of mechanical modification

is shown in FIG. 6A, where the LED (shown at far left with a rectangular, arched-top lens) is modified to include a keyed offset 601 on its holder 606, and accordingly, the LED lamp base 605 incorporates a notch 602 to accommodate this keyed offset. This first pair of modifications, useful for manufacturing only, results in the LED being properly mounted within its base to form replaceable LED lamp bulb. In order to properly fit this replaceable LED lamp bulb into its holder on the light string, the lamp base is also modified to include a keyed offset 603 on its base 605, and the lamp assembly holder 607 is correspondingly notched 604 for proper alignment. This second pair of modifications is useful in both manufacturing and by the user, for properly placing or replacing the LED lamp bulb into its holder on the light string. The LED lamp base and holder collectively form the LED housing. Note that such a mechanical arrangement makes it physically impossible to incorrectly insert the LED. FIG. 6B is a top view of the lamp base taken along viewing line 6B-6B of FIG. 6A.

In manufacturing the above modification to assure proper LED polarity, it may be advantageous to build the LED mold such that two piece replaceable LED lamp bulb described in FIG. 6 can be made in one step as a single piece. This is illustrated in FIG. 7, where the single piece replaceable LED lamp bulb 701 has a single keyed offset to fit into its notched lamp holder 702. Although this requires more elaborate modification of the LED base, the resulting assembly is now composed of two, rather than three, LED pieces and as such, may allow the lights string to be made more rapidly and at lower cost.

Typically, the LEDs in the light string will incorporate a lens for wide-angle viewing. However, it is also possible to attach fiber optic bundles or strands to the LEDs to spatially diffuse the LED light in a predetermined way for a desirable visual effect. In

such case, the LED lens is designed to create a narrow-angle light beam (e.g., 20 degree beamwidth or less) along its axis, to enable the LED light to flow through the fiber optics with high coupling efficiency. An example of the use of fiber optics is shown in FIG. 8, where a very lossy fiber optic rod is employed with intention for the fiber optic rod to glow like an illuminated "icicle." In FIG. 8, the LED 801 and its housing 802 may be attached to the fiber optic rod 803 using a short piece of tubing 804 that fits over both the LED lens and the end of the fiber optic rod (note that the drawing is not to scale). An example design uses a cylindrical LED lens with a narrow-angle end beam, where the diameter of the LED lens and the diameter of the fiber optic rod are the same (e.g., 5 mm or 3/16 inches). The fiber optic rod 803 is typically between three to eight inches in length and may be either uniform in length throughout the light string, or the fiber optic rod length may vary in either a periodic or pseudo-random fashion.

Although the fiber optic rod 803 in FIG. 8 could be constructed using a variety of plastic or glass materials, it may be preferred that the rod is made in either a rigid form using clear Acrylic plastic or clear crystal styrene plastic, or in a highly flexible form using highly plasticized Polyvinyl Chloride (PVC). These plastics are preferred for safety, durability, light transmittance, and cost reasons. It may be desirable to add into the plastic rod material either air bubbles or other constituents, such as tiny metallic reflectors, to achieve the designed measure of lossiness for off-axis glowing (loss) versus on-axis light conductance. Moreover, it is likely to be desirable to add UV inhibiting chemicals for longer outdoor life, such as a combination of hindered amine light stabilizer (HALS) chemicals. The tubing 804 that connects the fiber optic rod 803 to its LED lens 801 may also made from a variety of materials, and be specified in a variety of ways according to

opacity, inner diameter, wall thickness, and flexibility. From safety, durability, light transmittance, and cost reasons, it may be preferred that the connection tubing 804 be a short piece (e.g., 10 mm in length) of standard clear flexible PVC tubing (containing UV inhibiting chemicals) whose diameter is such that the tubing fits snugly over both the LED lens and the fiber optic rod (e.g., standard wall tubing with 1/4 inch outer diameter). An adhesive may be used to hold this assembly more securely.

The method of determining and calculating the preferred LED network that provides stable and functioning operation will now be described.

Many current-limiting designs use a single impedance element in series between the LED network and the power supply. Current-saturated transistors are a less common method of current limiting. A resistor is often used for the impedance element due to low cost, high reliability and ease of manufacture from semiconductors. For pulsed-DC or AC power, however, a capacitor or inductor may instead be used for the impedance element. With AC power, even though the waveform shape may be changed by capacitors or inductors, the overall effect of these reactive elements is basically the same as a resistor, in adding constant impedance to the circuit due to the single AC frequency involved (e.g., 60 Hz). In any case, the fundamental effect of current-limiting circuitry is to partially linearize or limit the highly nonlinear current versus voltage characteristic response curve of the diode, as shown in Figure 9 for a single resistor element.

Figure 10 shows the preferred embodiment of the invention, wherein a network of diodes, consisting of LEDs, is directly driven by the AC source without any current-limiting circuitry. The top diagram is a general schematic diagram showing M series blocks of LEDs directly connected in parallel to the AC source where, for the m-th series

block, there are N_m $\{1 \leq m \leq M\}$ LEDs directly connected to each other in series. Also shown is a reversal of polarity between some series blocks, placing these blocks in opposite AC phase, in order to minimize peak current in the overall AC circuit. The bottom diagram in Figure 10 is a block diagram of the above schematic, where a combination plug/socket is drawn explicitly to show how multiple devices can be directly connected either on the same end or in an end-to-end fashion, without additional power supply wires in between. This end-to-end connection feature is particularly convenient for decorative LED light strings.

The invention in Figure 10 may have additional circuitry, not explicitly drawn, to perform functions other than current-limiting. For example, logic circuits may be added to provide various types of decorative on-off blinking. A full-wave rectifier may also be used to obtain higher duty factor for the diodes which, without the rectifier, would turn on and off during each AC cycle at an invisibly high rate (e.g., 50 or 60 Hz). The LEDs themselves may be a mixture of any type, including any size, shape, material, color or lens. The only vital feature of the diode network is that all diodes are directly driven from the AC power source, without any form of current-limiting circuitry.

In order to directly drive a network of diodes without current-limiting circuitry, the voltage of each series block of diodes must be matched to the input source voltage. This voltage matching requirement for direct AC drive places fundamental restrictions on the number of diodes on each diode series block, depending on the types of diodes used. For the voltage to be "matched," in each series block, the peak input voltage, V_{peak}, must be less than or equal to the sum of the maximum diode voltages for each series block. Mathematically, let V_{peak} be the peak voltage of the input source and let $V_{max}(n,m)$ be the

maximum voltage for the n-th diode $\{1 \le n \le N_m\}$ of the m-th series block $\{1 \le m \le M\}$. Then, for each m, the peak voltage must be less than or equal to the m-th series block voltage sum,

$$V_{peak} \le \sum_n V_{max}(n,m) \qquad (1)$$

where $\{1 \le n \le N_m\}$ in the sum over n. For simpler cases where all N_m diodes in the m-th series block are of the same type, each with V_{max}, then $V_{peak} \le N_m V_{max}$.

The maximum voltage V_{max} of each diode is normally defined by the voltage which produces diode maximum current, I_{max}. However, when diodes of different types are used in a series block, the series block value of I_{max} is the *minimum* of all individual diode values for I_{max} in the series block. Thus, if the m-th series block has N_m diodes, with the n-th diode in the m-th series block having maximum current $I_{max}(n,m)$, then the value of I_{max} for the m-th series block, $I_{max}(m)$, is determined by the minimum of these N_m individual diode values,

$$I_{max}(m) = \min[I_{max}(n,m)\ ;\ \{1 \le n \le N_m\}]. \qquad (2)$$

The maximum voltage V_{max} of each diode in the m-th series block is thus defined as the voltage which produces the m-th series block maximum current $I_{max}(m)$. For simpler cases where all diodes in a series block are of the same type, each with maximum current I_{max}, then $I_{max}(m) = I_{max}$.

For AC or any other regularly varying input voltage, there is an additional requirement to direct drive voltage matching. Here, in a similar way to peak voltage above, the average, or RMS, voltage of the source, V_{rms}, must also be less than or equal to

the sum of the average diode voltages, V_{avg}, for each series block. Mathematically, let V_{rms} be the RMS voltage of the input source and let $V_{avg}(n,m)$ be the average forward voltage for the n-th diode $\{1 \leq n \leq N_m\}$ of the m-th series block $\{1 \leq m \leq M\}$. Then, for each m, the RMS voltage must be less than or equal to the m-th series block voltage sum,

$$V_{rms} \leq \sum_n V_{avg}(n,m) \qquad (3)$$

where $\{1 \leq n \leq N_m\}$ in the sum over n. For simpler cases where all N_m diodes in the m-th series block are of the same type, each with V_{rms}, then $V_{rms} \leq N_m V_{avg}$.

In a similar way to the peak voltage above, the average voltage of each diode, V_{avg} is normally defined by the voltage which produces diode average current, I_{avg}. However, when diodes of different types are used in a series block, the series block value of I_{avg} is the minimum of all individual diode values for I_{avg} in the series block. Thus, if the m-th series block has N_m diodes, each with average current $I_{avg}(n,m)$ then the value of I_{avg} for the M-th series block, $I_{avg}(m)$, is determined by the minimum of these N_m values,

$$I_{avg}(m) = \min[I_{avg}(n,m)\ ;\ \{1 \leq n \leq N_m\}]. \qquad (4)$$

The average voltage V_{avg} of each diode in the m-th series block is thus defined as the voltage which produces the m-th series block average current $I_{avg}(m)$. For simpler cases where all diodes in a series block are of the same type, each with average current I_{avg}, then $I_{avg}(m) = I_{avg}$.

Note that the term “average”, rather than “RMS,” is used to distinguish RMS diode values from RMS input voltage values because diode values are always positive (nonnegative) for all positive or negative input voltages considered, so that diode RMS

values are equal to their simple averages. Note also that in past LED designs, the specified DC value for I_{nom} is equated to the average diode value, I_{avg}. LEDs are always specified in DC, and the specified DC value for I_{nom} results from a tradeoff between LED brightness and LED longevity. In the direct AC drive analysis below, this tradeoff between brightness and longevity results in values for I_{avg} that are generally different than I_{nom}. The direct AC drive value for V_{avg} is thus also generally different than the LED specified DC value V_{nom}.

LEDs are specified in terms of DC values, V_{nom} and I_{nom}. For AC power, since V_{avg} is an AC quantity and V_{nom} is a DC quantity, they are fundamentally different from each other. This basic difference between AC and DC values arises from the nonlinear relationship between diode voltage and diode current. Consider AC voltage input to a diode as shown for one period in Figure 11, where the peak voltage shown, V_{pk}, is less than or equal to the diode maximum voltage, V_{max}. For AC voltages below the diode voltage threshold, V_{th}, the current is zero. As the voltage increases above V_{th} to its peak value, V_{pk}, and then falls back down again, the diode current rises sharply in a nonlinear fashion, in accordance to its current versus voltage characteristic response curve, to a peak value, I_{pk}, and then the diode current falls back down again to zero current in a symmetric fashion. Since the voltage was chosen such that $V_{pk} \leq V_{max}$, then the peak diode current satisfies $I_{pk} \leq I_{max}$. The average diode current, I_{avg}, is obtained by integrating the area under the current spike over one full period.

The central problem of AC voltage matching in equations (1) through (4) for direct drive of diodes is to first determine peak AC diode current, I_{peak} and average AC diode current, I_{avg}, as a function of V_{rms} or, equivalently, the peak AC voltage

$V_{peak} = \sqrt{2}\ V_{rms}$. Since the nonlinear relationship for diode current versus voltage is not known in closed form, these diode AC current versus input AC voltage relationships cannot be obtained in closed form. Moreover, the nonlinear diode AC current versus input AC voltage relationships vary for different diode types and materials. In all cases, since the diode current versus voltage characteristic curve, near the practical operating point V_{nom}, is a convex-increasing function, i.e., its slope is positive and increases with voltage, the average diode current I_{avg} that results from a given RMS value of AC voltage is always higher than the diode current that would be achieved for a DC voltage input having the same value. Because of this, specified DC values for diode voltage cannot be directly substituted for AC diode voltage values. Instead, the characteristic diode AC current versus input AC voltage relationships must be found for the AC waveform of interest.

The characteristic diode AC current versus voltage relationships may be found by *measuring* diode current values I_{avg} and I_{peak} as a function of RMS voltage, V_{rms}, using variable voltage AC source. A number of alike diodes are used in these measurements to obtain good statistics. If different diode types or materials are considered, then each measurement procedure is repeated accordingly. Figure 12 shows a typical measurement result for average current, I_{avg}, where the diode used has specified nominal values of $V_{nom} = 2$ VDC and $I_{nom} = 20$ mA.

The average AC current curve is always to left of the DC current curve in Figure 12. Thus, Figure 12 shows that if one used DC voltages for the diode in an AC circuit, the resulting average AC diode current would be much higher than the DC current expected. Recall that in the prior art, where a number of alike 2 VDC LEDs are

connected in series with a current-limiting resistor, a maximum number N of LEDs is defined by summing the individual LED voltages and equating to the RMS input voltage. For a 120 VAC source, this maximum number is N = 60 LEDs. The prior art then subtracts five or ten LEDs from this maximum to obtain a design number, and computes the resistor value using the difference between the AC input RMS voltage and the sum of these DC LED voltages. This design is marginally stable, and then becomes unstable, as the number of LEDs subtracted becomes smaller. Instability is proven in Figure 12, by considering the limit case where a maximum number N = 60 of LEDs are used and hence no LEDs are subtracted. In this limit case, one might argue that a resistor must be used anyway, but according to this design formula, presented for five or ten LEDs subtracted, the resistor value in this case would equal zero. As Figure 12 shows, if the resistor value were zero, i.e., the resistor is omitted, instead of the DC design value of I_{nom} = 20 mA for LED current (the rightmost, DC, curve at 2.0 VDC), the LED average AC current will be off the scale, higher than the maximum diode current I_{max} = 100 mA (the leftmost, AC, curve at 1.87 VAC), and the device will fail immediately or almost immediately.

In order to properly perform matching in an direct AC drive design, the characteristic diode AC current versus input AC voltage relationships must be measured and used to specify the AC values for equations (1) through (4). DC specifications and DC diode measurements cannot directly be used in the direct AC drive design, and they are useful only as a guide for theoretical inference, discussed further below. Along with the diode average AC current, the diode peak AC current must also be measured as a function of RMS (or equivalently, peak) input AC voltage. Figure 13 shows a typical

measurement result, where the diode used has specified DC nominal values of $V_{nom} = 2$ VDC and $I_{nom} = 20$ mA.

As stated previously, for an AC design, the LED average AC current, I_{avg}, is generally different from the specified LED nominal DC current, I_{nom}. Likewise, the LED maximum AC current, I_{max}, is also generally different from the specified LED maximum DC current. Choice of these values represent a tradeoff between LED brightness and electrical efficiency versus LED longevity. In general for pulsed-DC or AC input, the LED is off at least part of the time and is therefore has time to cool during off-time while heating during on-time. In order to increase light output and hence electrical efficiency, both the average and the peak diode current values can be raised somewhat above specified DC values and maintain the same longevity, which is defined as the total on-time until, say, 30% loss of light output is incurred – typically at about 100,000 on-time hours. Moreover, these LED average and peak current values can be raised further to increase light output and electrical efficiency at some expense in LED longevity, depending on the on-time duty factor. Higher ambient temperatures are accounted for by lowering, or "derating" these values somewhat.

In a publication by Hewlett Packard, a number of curves are presented of projected long term light output degradation, for various pulsed-DC duty factors and various average and peak current values, at ambient temperature $T_A = 55°$ C. The AlInGaP LEDs used in this data represents the material commonly used in an LED with specified DC nominal voltage $V_{nom} = 2$ VDC. While results vary somewhat for other LED materials, it can be inferred from this data that, for most LEDs specified at $I_{nom} = 20$ mA, the AC design choice for I_{avg} is approximately in the interval,

$$30\ \text{mA} \le I_{avg} \le 50\ \text{mA} \tag{5}$$

where the specific value chosen, $I_{avg} = 36$ mA, is indicated in Figure 13.

Similarly, from the Hewlett Packard data it can be inferred that, for most LEDs with maximum DC current specified at 100 mA, and the AC design choice for I_{max} is approximately,

$$I_{max} \le 120\ \text{mA} \tag{6}$$

where a specific value chosen of $I_{max} = 95$ mA satisfying this, that corresponds to $V_{avg} = 1.6$ VAC and $I_{avg} = 36$ mA, is also indicated in Figure 13.

To clarify the direct AC drive design, consider again the simpler case where all N LEDs in a series block are of the same type, with each LED specified as before at $V_{nom} = 2$ VDC and $I_{nom} = 20$ mA. Moreover, let the input AC power be the U.S. standard value and assume $V_{rms} = 120$ VAC for voltage matching. With the above values for I_{max} and I_{avg}, the maximum and average LED voltages, V_{max} and V_{avg}, are determined using AC current versus voltage measurements in Figure 13 and simplified versions of equations (2) and (4), respectively. The minimum number N of LEDs is determined from these voltages using the input voltage $V_{peak} = \sqrt{2}\ V_{rms}$ and equations (1) and (3), for maximum and average voltage respectively. Since the value for $I_{max} = 95$ mA was chosen as a lower value than possible by equation (6), corresponding to $V_{avg} = 1.6$ VAC and $I_{avg} = 36$ mA, the maximum voltage becomes $V_{max} = \sqrt{2}\ V_{avg}$ and equation (1) is automatically satisfied by satisfying equation (3). Solving equation (3) results in the minimum number of N LEDs as,

$$V_{rms} \le N\ V_{avg} \quad \Rightarrow \quad 120 \le N\,(1.6) \quad \Rightarrow \quad N \ge 75 \tag{7}$$

Although the value of $N = 75$ is a convenient number to use for manufacturing and sale of a decorative LED light string, if a different, less convenient, minimum number N of LEDs were computed, the result can be rounded up or down slightly for convenience, provided that the subsequent changes in LED brightness or longevity are acceptable. For example, if the RMS voltage were assumed to be 110 VAC, then the resulting minimum number of LEDs in equation (7) would be $N \geq 69$, and this value may be rounded to a final value of $N = 70$ for convenience, with only slight impact on LED brightness.

Efficiency of the above direct AC drive design example can be estimated by first noting that the average power, P_{avg}, consumed by a single LED in the series block is the product of the average voltage and the average current, $P_{avg} = V_{avg} I_{avg}$. This is compared against the optimal DC baseline that uses the specified DC nominal LED power consumption, P_{nom}, defined as the product of the nominal voltage and the nominal current, $P_{nom} = V_{nom} I_{nom}$. Using the values given in the above direct AC drive example, there results, $P_{avg} \approx 1.44 P_{nom}$, so that the direct AC drive design consumes 44% more power per LED than the DC baseline. However, to examine efficiency, first let L_{avg} be the average light output power for the direct AC drive design and L_{DC} be the optimal light output power using the DC baseline. This light output power L represents LED efficiency as a device, i.e., how much light the LED can be made to produce. Defining relative device efficiency as the quotient $\varepsilon_D = L_{avg} / L_{DC}$ enables the amount of light produced by each LED in direct AC drive design to be compared with the optimal DC baseline. Using an approximation that the LED light output power, L, is proportional to the LED current, I, this LED device efficiency, ε_D, is approximately,

$$\varepsilon_D = L_{avg} / L_{DC} \approx I_{avg} / I_{nom} = 36 / 20 = 1.8 \qquad (8)$$

so that the direct AC design example makes about 80% more use of each LED as a light producing device than the optimal DC baseline. In other words, for each LED used, the direct AC drive design produces about 80% more light than the maximum possible by a DC design based on nominal LED values. Although this factor of 80% light increase appears to be large, its effect is diminished by human perception. According to the well known law by Stevens, human perceptions follow a continuum given by the power relationship,

$$B \propto L^{\rho} \qquad (9)$$

where L is the stimulus power, B is the perceived brightness intensity, and exponent ρ is a parameter that depends on the type of stimulus. For light stimuli, L is the light power in Watts, B is the perceived photopic brightness in lumens, and the exponent is approximately $\rho \approx {}^1/_3$. With this exponent, the 80% increase in light output power offered by the direct AC design example translates into about 22% increase in perceived brightness. Although a smaller realized effect, the direct AC design example does offer an increase, rather than a decrease, in brightness relative to the optimal DC baseline.

LED electrical efficiency, E, is defined by dividing light output power by electrical power used, $E = L / P$. Defining relative electrical efficiency as the quotient $\varepsilon_E = E_{avg} / E_{DC}$ enables the electrical efficiency in direct AC drive design to be compared with the optimal DC baseline. Using again an approximation that the LED light output power, L, is proportional to the LED current, I, there follows,

$$\varepsilon_E \approx (I_{avg} / P_{avg}) / (I_{nom} / P_{nom}) = V_{nom} / V_{avg} = 2.0 / 1.6 = 1.25 \qquad (10)$$

so that the AC direct drive design is about 25% more electrically efficient than the optimal DC baseline. In other words, for a fixed amount of input power, the direct AC design examples produces about 25% more light than the maximum possible by DC based on nominal LED values.

There are two basic reasons for the results in equations (8) and (10). First, the direct drive design does not have current-limiting circuitry to consume power. If this were the only factor involved, the direct AC design efficiency would be 100%, relative to the optimal DC baseline, because the optimal DC baseline is computed without current-limiting circuitry loss. The second basic reason stems from the nonlinear relationship between LED current and voltage. Because this relationship is a convex-increasing function, i.e., its slope is positive and increases with voltage, average AC diode current I_{avg} is always higher than DC current for the same voltage value. This higher AC average current in turn leads to higher average light output, with an approximation showing a proportional relationship. This is a fundamental advantage to the pulsed waveforms over DC that others fail to recognize for AC and instead try to avoid. The nonlinear current versus voltage relationship is further taken advantage of in the direct AC drive design by increasing the average current to a more optimal value, using the fact that the LED has time to cool during the off-time interval in each AC cycle.

An approximation that LED light output is proportional to LED current is very close for most operating values of LED current, but the approximation usually overestimates light output at high current values. A typical curve for AlInGaP LEDs, the common material type for LEDs with a 2 VDC specification, is shown in Figure 14. With this measured result, the relative direct AC drive efficiencies computed in equations

(8) and (10) are lowered somewhat, but they are still well above unity. A numerical integration using Figure 14 indicates that equations (8) and (10) overestimate efficiency of the direct AC design in the example presented by about 15%, and closer estimates for the above relative efficiencies are $\varepsilon_D \approx 1.53$ and $\varepsilon_E \approx 1.06$.

Diminishing light output power at high LED current places the optimal value for RMS and peak LED current values, I_{avg} and I_{max}, at a slightly lower value than the average and peak current constraints in equations (5) and (6) allow. For example, Figure 13 shows that the largest value allowed by equations (5) and (6) for V_{avg} is 1.65 VAC, rather than the value of 1.60 VAC used above. This larger value of V_{avg}=1.65 VAC, achieved by N = 72 LEDs in a 120 VAC series block, is slightly less efficient, as well as slightly less reliable, than the value of V_{avg} = 1.60 VAC and N = 75 LEDs. However, the value of N = 72 LEDs in the series block would cost less to produce per unit. Using 110 VAC instead of 120 VAC to obtain a lower number N = 69 LEDs in the series block yields yet slightly lower efficiency and reliability still. For decorative LED light strings, this final direct AC drive tradeoff between, say, 70 versus 75 LEDs in the series block exemplified is a matter of practical judgment to provide the highest quality product at the lowest unit cost.

Although it has been shown above that LED specified DC values cannot be directly used in for direct AC drive, these values do have some theoretical utility for using a smaller measurement set to estimate the AC design values. The theoretical basis of this estimation procedure results from applying statistical inference on the LED specifications, using these specifications in a different way than they are obtained or intended.

LEDs are specified by two voltage parameters, a typical, or "nominal" voltage, V_{nom}, and a largest, or "supremum" (usually called "maximum" by LED manufacturers) voltage, V_{sup}. These specifications are obtained as *ensemble* estimates, for a large ensemble of alike LEDs, of "typical" and "largest" DC voltages to expect, from variations due to manufacturing, that produce the chosen nominal value of DC current, I_{nom}. The nominal DC voltage, V_{nom}, is intended as a "typical" value for the LED, obtained either by averaging measurements or by taking the most likely, or modal, value in a measurement histogram. The maximal DC voltage, V_{sup}, is intended as a largest, or "supremum," value for the LED, obtained by sorting the largest voltage value measured that produces the chosen nominal value of DC current, I_{nom}.

The theoretical problem of interest is to obtain values for average AC voltage, V_{avg}, and maximum AC voltage, V_{max}, that produce average AC current, I_{avg} and maximum AC current, I_{max}, respectively. These voltage values V_{avg} and V_{max} do not consider LED ensemble variations due to manufacturing but instead rely on a large enough number N of LEDs in each AC series block for manufacturing variations to be averaged over. Otherwise, voltage equations (1) and (3) above must be altered slightly to account for expected LED manufacturing variations. Such an alteration would rely on a statistical model obtained by measuring variations of the characteristic AC current versus AC voltage curve, from LED to LED in a large ensemble of alike LEDs. In any event, the voltages V_{avg} and V_{max} are fundamentally defined to represent *characteristic* estimates of voltage for varying values of LED current, obtained by averaging over the ensemble, rather than *ensemble* estimates, using individual LEDs within the ensemble, of voltages that produce a fixed, say, nominal, value of LED current.

In order to make theoretical inferences from LED specifications, it must be assumed that the specified *ensemble* random variables representing "nominal" and "supremum" voltages can be interchanged with equivalent *characteristic* random variables representing corresponding voltages that produce corresponding LED current over time. This assumption is similar to a commonly assumed form of ergodicity in random process theory that interchanges ensemble random variables with corresponding time-series random variables.

With this ergodicity assumption, the AC average and maximum voltage values of interest, V_{avg} and V_{max}, can be inferred from the specified diode values for DC nominal and maximum voltage, V_{nom} and V_{sup}, respectively, using appropriate DC-to-AC scaling between them. It is desired to obtain a single scale factor α for all LED materials, colors, and LED manufacturers. In trying to find this single value for scale factor α, difficulty arises in that the specified voltages, V_{nom} and V_{sup}, are fundamentally different for different LED dopant materials. However, given a specific LED dopant material "M", such as AlInGaP or GaAlAs, the variations in V_{nom} and V_{sup} across applicable colors and manufacturers are small enough to be considered fairly insignificant.

Recall that V_{max} is equated with peak input voltage V_{peak} in equation (1), and V_{avg} is equated with RMS input voltage V_{rms} in equation (3). For AC power, the quotient $V_{peak} / V_{rms} = \sqrt{2}$. It would thus be desirable if the quotient V_{sup} / V_{nom} were also always a constant, preferably equal to $\sqrt{2}$, so that a single scale factor α_M could be used for each LED material, "M." Unfortunately, this ratio also varies significantly for different LED materials. As a result, two distinct scale factors α_M and β_M are required for each LED

material composition, "M." With these material-dependent scale factors, α_M and β_M, the AC voltages of interests are estimated from DC specified values using,

$$V_{avg} \approx \alpha_M V_{nom}, \quad V_{max} \approx \beta_M V_{sup}. \tag{11}$$

where the scale factors α_M and β_M are determined by measurement. The advantage provided by this theoretical estimation procedure is that the set of measurements determining characteristic curves for peak and average AC current versus AC voltage need only be obtained for each LED dopant material, independent of LED color and LED manufacturer. Of course, the disadvantage to this procedure is that it is approximate when compared to making full measurement sets for all specific types of LEDs considered, and hence some experimentation with the exact number of LEDs is required.

For AlInGaP LEDs, $V_{nom} = 2.0$ VDC and $V_{sup} = 2.4$ VDC represent the centroids of specified values across applicable colors and from various manufacturers. The characteristic curves presented in Figure 7 were obtained from AlInGaP LEDs. From Figure 13, and the criteria for average and maximum AC current defined in equations (5) and (6), respectively, AC current values $I_{avg} = 36$ mA and $I_{max} = 95$ mA were chosen previously, with $V_{max} = \sqrt{2}\, V_{avg}$ and $V_{avg} = 1.6$ VAC. Equations (11), then, lead to $\alpha_{AlInGaP} = 0.80$ and $\beta_{AlInGaP} = 0.94$. These values may be used theoretically in equations (11) to estimate approximate AC average and maximum voltages, V_{avg} and V_{max}, for other AlInGaP LEDs.

Figure 15 shows measured characteristic curves for a different set of alike LEDs, where the dopant material is GaAlAs, rather than AlInGaP. For GaAlAs LEDs, $V_{nom} = 1.7$ VDC and $V_{sup} = 2.2$ VDC represent the centroids of specified values across

applicable colors and from various manufacturers. From Figure 15, and the criteria for average and maximum AC current defined in equations (5) and (6), respectively, AC current values $I_{avg} = 38$ mA and $I_{max} = 95$ mA are chosen, with again $V_{max} = \sqrt{2}\, V_{avg}$, but now $V_{avg} = 1.45$ VAC. Equations (11), then, lead to $\alpha_{GaAlAs} = 0.85$ and $\beta_{GaAlAs} = 0.93$. These values may be used theoretically in equations (11) to estimate approximate AC average and maximum voltages, V_{avg} and V_{max}, for other GaAlAs LEDs. Note that, with 120 VAC assumed for the RMS input voltage, this value $V_{avg} = 1.45$ VAC leads to N = 83 LEDs per series block. Similarly, with 110 VAC assumed for the RMS input voltage, N = 76 LEDs per series block. Rounding these values leads to either 75, 80, or 85 LEDs per series block in a manufactured product, with N = 75 being most desirable for a decorative LED light string from a cost basis, if it is sufficiently reliable.

The above direct AC drive design procedure has been verified by building numerous decorative LED light string prototypes using a variety of dopant materials, colors, and manufacturers. Many of these prototypes were built as long as two years ago, and all prototypes have remained operating continuously without any sign of impending failure. Moreover, a number of these prototypes were subjected to harsh voltage surge and voltage spike conditions. Voltage surge conditions were produced using high power appliances in the same circuit, all of which failed to produce anything other than at most some flickering. In about half of these experiments the voltage surges created caused circuit breakers to trip. The decorative LED light string prototypes, being waterproof, were also immersed in water during testing.

Voltage spikes, simulating lightning discharges, were produced by injecting 1000 V, 10 A pulses of up to 10 ms duration and one second apart into a 100 A main circuit of

a small home using a pulse generator and 10 kW power amplifier. The amplifier was powered from the main electrical input of an adjacent home. During these tests, all decorative LED light string prototypes merely flickered in periodic succession at one second intervals. In the meantime during these tests, the protective circuitry of adjoining electronic equipment shut off without any ensuing damage. All these tests verified conclusively that the decorative LED light strings were designed to be highly reliable by the direct AC drive method, without the use of any current-limit circuitry.

It will be understood that various changes in the details, materials and arrangements of the parts which have been described and illustrated in order to explain the nature of this invention may be made by those skilled in the art without departing from the principle and scope of the invention as expressed in the following claims.